Optimization of Phase Feeding of Starter, Grower, and Finisher Diets for Male Broilers by Mixture Experimental Design: Forty-Eight-Day Production Period

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ABSTRACT A mixture experiment, a variant of response surface methodology, was designed to determine the proportion of time to feed broiler starter (23% protein), grower (20% protein), and finisher (18% protein) diets to optimize production and processing variables based on a total production time of 48 d. Mixture designs are useful for proportion problems where the components of the experiment (i.e., length of time the diets were fed) add up to a unity (48 d). The experiment was conducted with day-old male Ross × Ross broiler chicks. The birds were placed 50 birds per pen in each of 60 pens. The experimental design was a 10-point augmented simplex-centroid (ASC) design with 6 replicates of each point. Each design point represented the portion(s) of the 48 d that each of the diets was fed. Formulation of the diets was based on NRC standards. At 49 d, each pen of birds was evaluated for production data including BW, feed conversion, and cost of feed consumed. Then, 6 birds were randomly selected from each pen for processing data. Processing variables included live weight, hot carcass weight, dressing percentage, fat pad percentage, and breast yield (pectoralis major and pectoralis minor weights). Production and processing data were fit to simplex regression models. Model terms determined not to be significant ($P > 0.05$) were removed. The models were found to be statistically adequate for analysis of the response surfaces. A compromise solution was calculated based on optimal constraints designated for the production and processing data. The results indicated that broilers fed a starter and finisher diet for 30 and 18 d, respectively, would meet the production and processing constraints. Trace plots showed that the production and processing variables were not very sensitive to the grower diet.

(*Key words*: broiler, mixture design, phase feeding, response surface)

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INTRODUCTION

Previous research has shown that the time of providing diets has a significant effect on the economics, growth, and uniformity of broilers (Gehle et al., 1974; Brown and McCartney, 1982; Skinner et al., 1992; Saleh et al., 1996, 1997a,b; Warren and Emmert, 2000; Pope and Emmert, 2001; Vandegrift, 2002; Vandegrift et al., 2003). Diet provision has been evaluated with a response surface design (Roush, 1983). However, treating diet provision as a mixture is a new approach. For a given time period (e.g., 48 d), the proportion of time that birds are provided individual diets can be conceptualized as a mixture design, which is a variant of a response surface design.

Mixture designs are useful for proportion problems where the components of the experiment add up to a unity or a mixture. A simple mixture example would be the determination of the optimal proportion of ingredients (e.g., flour, eggs, sugar) to make a cake. The equation describing a mixture design does not include the intercept, which allows the equation to represent a unity for the ingredients. Cornell (2002) provides an extensive reference on the use of mixture designs.

The first application of a mixture design was by Claringbold (1955) for hormone mixture studies with mice. Other applications of mixture designs have involved the blending of rocket propellants (Kurotori, 1966), gasoline mixtures (Snee, 1981), and fruit drink mixtures (Huor et al., 1980). Gous and Swatson (2000) have used mixture designs to study broiler self-selection of dietary ingredients. Time of diet change can be considered a mixture experiment where starter (S), grower (G), and finisher (F) diets are fed to birds for a proportion of time. In this experiment, the time periods that the animals were fed

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Abbreviation Key: ASC = augmented simplex-centroid; F = finisher diet; G = grower diet; LOF = lack-of-fit; POE = propagation of error; S = starter diet.

TABLE 1. Ingredients and calculated analysis of broiler diets used in the mixture design

Ingredient (%)	Starter	Grower	Finisher
Corn	48.261	60.969	69.509
Soybean meal	30.245	22.722	17.655
Alfalfa meal	6.138	4.379	3.196
Poultry by-product meal	5.000	5.000	5.000
Poultry fat	7.062	4.312	2.468
Dicalcium phosphate	1.475	0.728	0.498
Limestone	0.972	1.239	1.175
Salt	0.303	0.247	0.168
DL-Methionine	0.219	0.079	0.006
Vitamin-mineral premix[1]	0.250	0.250	0.250
Coban	0.075	0.075	0.075
Total	100.000	100.000	100.000
Calculated analysis			
ME (kcal/kg)	3,200	3,200	3,200
CP (%)	23	20	18
CP (%, chemical analysis)	23.2	20.0	18.1
Calcium (%)	1.0	0.9	0.8
Available phosphorus (%)	0.5	0.35	0.30
Methionine + cysteine (%)	0.93	0.72	0.60
Lysine (%)	1.23	1.01	0.87
Threonine (%)	0.97	0.84	0.75

[1]Premix provided the following per kilogram of diet: vitamin A, 7,716 IU; cholecalciferol, 2,205 IU; vitamin E, 9.9 IU; menadione, 0.88 mg; vitamin B_{12}, 0.01 mg; choline, 379 mg; riboflavin, 5 mg; niacin, 33 mg; d-pantothenic acid, 8.76 mg; thiamine, 0.99 mg; folic acid, 0.55 mg; d-biotin, 0.06 mg; pyridoxine, 0.88 mg; ethoxyquine, 0.03 mg; Mn, 55 mg; Zn, 50 mg; Fe, 27.5 mg; Cu, 7.72 mg; I, 1.1 mg; Se, 0.22 mg.

3 diets, S, G, and F, added up to 48 d. Simultaneous consideration of other time regimens (other than 48 d, for example) can be investigated, however, this would require another type of mixture approach called a mixture-amount experiment (Piepel and Cornell, 1985).

MATERIALS AND METHODS

Experimental Design

The objective of this experiment was to determine the optimal proportions of time broilers should be fed S, G, and F diets to optimize BW, feed conversion, carcass characteristics, and diet cost based on a total production time of 48 d. Compositions of S, G, and F rations (formulated by linear programming and based on NRC (1994) standards) are shown in Table 1. A 10-point augmented simplex-centroid (ASC) design (Khuri and Cornell, 1996) was selected for the mixture experiment. Table 2 lists the actual times and coded levels for the 10 combinations of S, G, and F diets specified by the ASC design. A graphical representation of ASC design is shown in Figure 1.

The experiment was conducted with 1-d-old male Ross × Ross broiler chicks. The chicks were weighed and placed 50 birds per pen (0.0836 m^2 per bird) in each of 60 floor pens with new pine shavings as bedding material. Six replicates of the 10-point ASC design were assigned as a randomized block experiment with 2 blocks represented by 30 pens in the upper and 30 pens in the lower ends of the house. Initial temperature was set at 35°C, and was reduced by 2.8°C per wk until 21.1°C was reached. The S, G, and F diets were fed as mash diets according to proportions of time (totaling 48 d) indicated in Table 2. Feed and water (via nipple drinkers) were provided ad libitum. Light was provided on a continuous basis.

TABLE 2. Mixture design (actual and coded levels) and control for phase feeding (48-d basis) starter, grower, and finisher diets to broilers: BW, feed conversion, and cost per ton of feed consumed data[1]

Design Point	Actual levels (d)			Coded levels			BW (kg)	Feed conversion	Cost/ton ($)[2]
	Starter	Grower	Finisher	Starter	Grower	Finisher			
1	48	0	0	1	0	0	2.731 ± 0.056	1.75 ± 0.01	168.80 ± 0
2	0	48	0	0	1	0	2.467 ± 0.082	1.85 ± 0.04	157.00 ± 0
3	0	0	48	0	0	1	1.978 ± 0.084	2.02 ± 0.02	150.00 ± 0
4	24	24	0	0.5	0.5	0	2.729 ± 0.047	1.81 ± 0.02	159.99 ± 0.09
5	24	0	24	0.5	0	0.5	2.530 ± 0.070	1.92 ± 0.02	154.81 ± 0.12
6	0	24	24	0	0.5	0.5	2.256 ± 0.042	1.96 ± 0.02	151.79 ± 0.02
7	16	16	16	0.333	0.333	0.333	2.572 ± 0.056	1.91 ± 0.02	154.57 ± 0.03
8	32	8	8	0.667	0.166	0.166	2.700 ± 0.081	1.87 ± 0.08	160.23 ± 0.21
9	8	32	8	0.166	0.667	0.166	2.439 ± 0.090	1.89 ± 0.02	155.50 ± 0.04
10	8	8	32	0.166	0.166	0.667	2.265 ± 0.048	2.00 ± 0.02	151.30 ± 0.05

[1]Mean ± SD, design points 1 to 10, n = 6.

[2]Feed consumed, cost per ton ($).

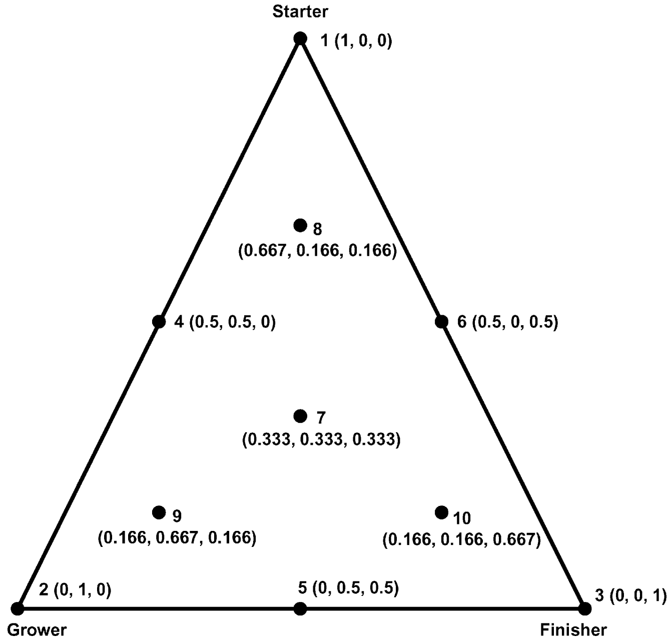

FIGURE 1. Ten-point augmented simplex-centroid mixture design with numbered design points and coded levels for starter, grower, and finisher diets, respectively.

Data Collection

On d 49, the birds and residual feed were weighed on a group (pen) basis. Feed conversion was calculated and corrected for the BW of mortality by including the weight of the birds that died in the BW gain. Carcass and meat yield processing data were determined from random samples of 6 birds from each pen (360 birds). The sampled birds were tagged, individually weighed, slaughtered, and processed at the Mississippi State University Poultry Processing facility. Measurements were made for hot carcass weight, dressing percentage (hot carcass weight/live weight × 100), fat pad percentage (fat pad weight/live weight × 100), and breast yield (pectoralis major and pectoralis minor). This experiment was conducted with the approval of the USDA/ARS Animal Care and Use Committee, Mississippi State Location (approval number 03-01).

Statistical Analyses Methods and Software

Scheffé mixture experiment models of the general form:

$$\hat{y} = b_S S + b_G G + b_F F + b_{SG} SG + b_{GF} GF + b_{SGF} SGF \quad [1]$$

were used to relate response variables $\hat{y}$, to proportional times of S, G, and F diets (where S + G + F = 1). The first terms in equation (1) represent linear blending effects of the S, G, and F components on a response $\hat{y}$, and comprise the Scheffé linear mixture model. The next 3 terms in equation (1) represent quadratic blending effects of S, G, and F. These 3 terms, along with the 3 linear terms, comprise the Scheffé quadratic mixture model. The complete model in equation (1) is referred to as the Scheffé special-cubic mixture model with the last term representing the special-cubic blending effect of S, G, and F diets on the response $\hat{y}$. Statistical tests of whether model coefficients are significantly different from zero are appropriate for the quadratic and special-cubic terms, but not for the linear terms. Quadratic and special-cubic model coeffi-

TABLE 3. Regression coefficient estimates for coded (SE) and actual values for phase feeding (48 d basis) of starter (S), grower (G), and finisher (F) broiler diets: BW, feed conversion, and cost per ton of feed consumed

	Regression coefficient estimate					
	BW (kg)		Feed conversion		Cost per ton of feed consumed ($)	
Component	Coded levels	Actual levels	Coded levels	Actual levels	Coded levels	Actual levels
Starter (S)	2.73 (0.028)	0.0570	1.76 (0.12)	0.0366	168.79 (0.041)	3.516
Grower (G)	2.46 (0.025)	0.0512	1.85 (0.012)	0.0386	157.04 (0.041)	3.272
Finisher (F)	1.99 (0.025)	0.0414	2.02 (0.013)	0.0421	150.00 (0.041)	3.125
SG	0.49 (0.13)	0.000214	—	—	–11.59 (0.21)	–0.00503
SF	0.71 (0.13)	0.000308	0.19 (0.062)	0.0000809	–18.37 (0.21)	–0.00797
GF	—	—	0.12 (0.062)	0.0000537	–6.77 (0.21)	–0.002939
SGF	—	—	—	—	3.63 (1.37)	0.0000328
Statistical values[1]						
Mean	2.47		1.90		156.40	
SD	0.071		0.034		0.10	
CV	2.86		1.80		0.067	
R^2	0.92		0.85		0.9996	
Adjusted R^2	0.91		0.84		0.9996	
Predicted R^2	0.91		0.83		0.9996	
MSE	0.04972		0.001162		0.011	
LOF *P*-value	0.0973 NS		0.1465 NS		<0.0001	
Adequate precision	36.8		26.5		524.68	

[1]MSE = mean square error; LOF = lack of fit.

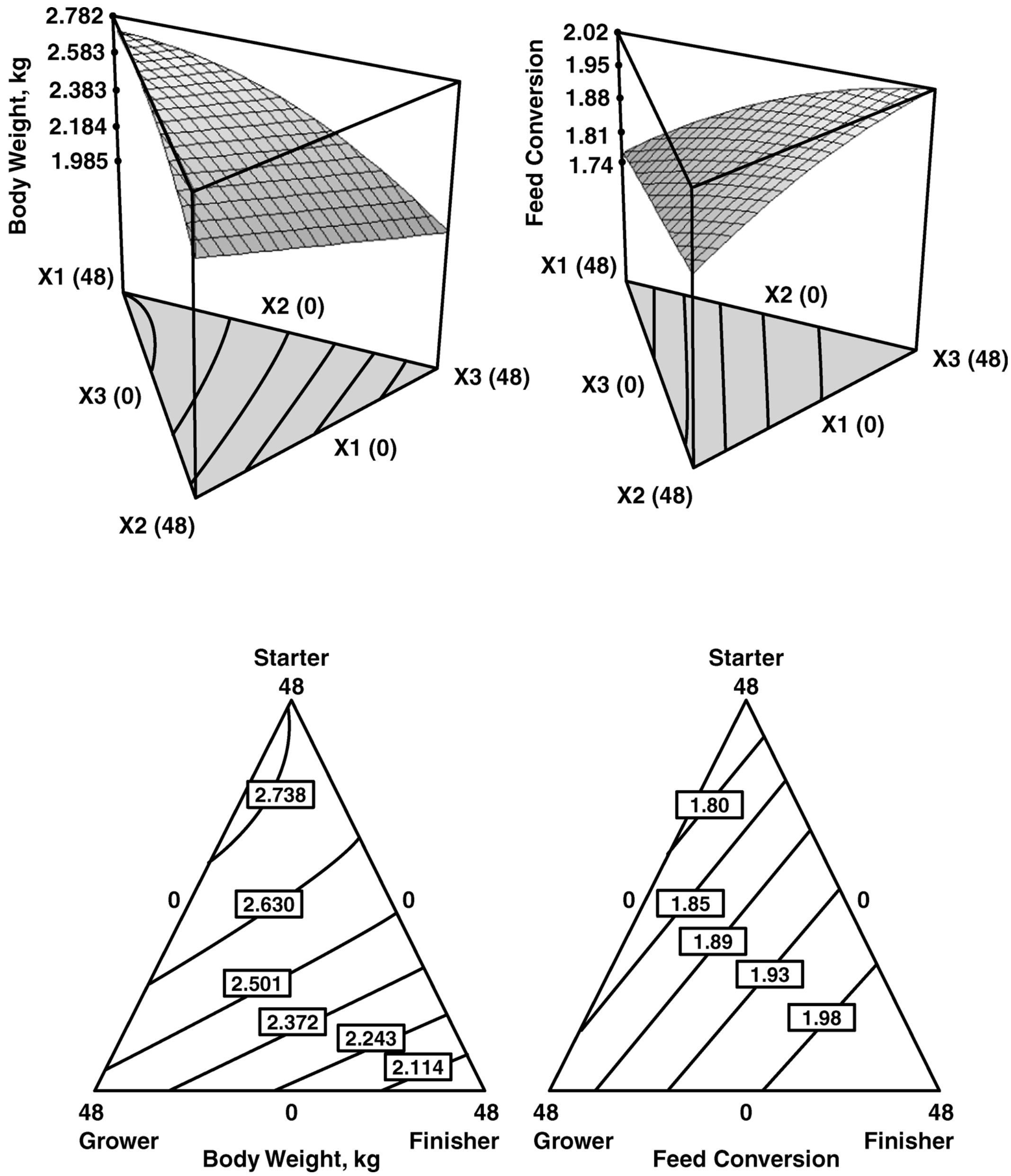

FIGURE 2. Three-dimensional response surfaces and two-dimensional contour plots for BW (kg) and feed conversion. Vertices represent starter (X_1), grower (X_2), and finisher (X_3) diets with a total production period of 48 d.

cients were considered to be statistically significant when P values <0.05 were obtained, unless otherwise noted.

Design-Expert (Stat-Ease, 2002) software was used for modeling and graphical analysis of the experimental data. Statistical guidelines concerning the analysis of mixture designs in the Design-Expert software were followed. Sequential model sum of squares were considered to choose between the linear, quadratic, and special-cubic model forms. Model lack-of-fit (LOF) tests were also performed by Design-Expert. For each response, the highest-order Scheffé model form containing significant terms and without a statistically significant LOF was selected. Nonlinear (i.e., special-cubic and quadratic) blending terms determined not to be statistically significant were not included in the selected model form.

Three-dimensional and contour graphs of the response surfaces were plotted based on the fitted mixture models. The response surface for the mixture blends is represented by the continuous nature of shape of the 3-D surface. The contour graph represents the response shape in 2 dimensions just as a geographical contour map represents the elevation of hills and valleys by contour lines.

Adequate precision, a measure of the contrast in predicted response relative to its associated error (i.e., signal to noise ratio) was assessed for each response model. Adequate precision ratios greater than 4 were considered

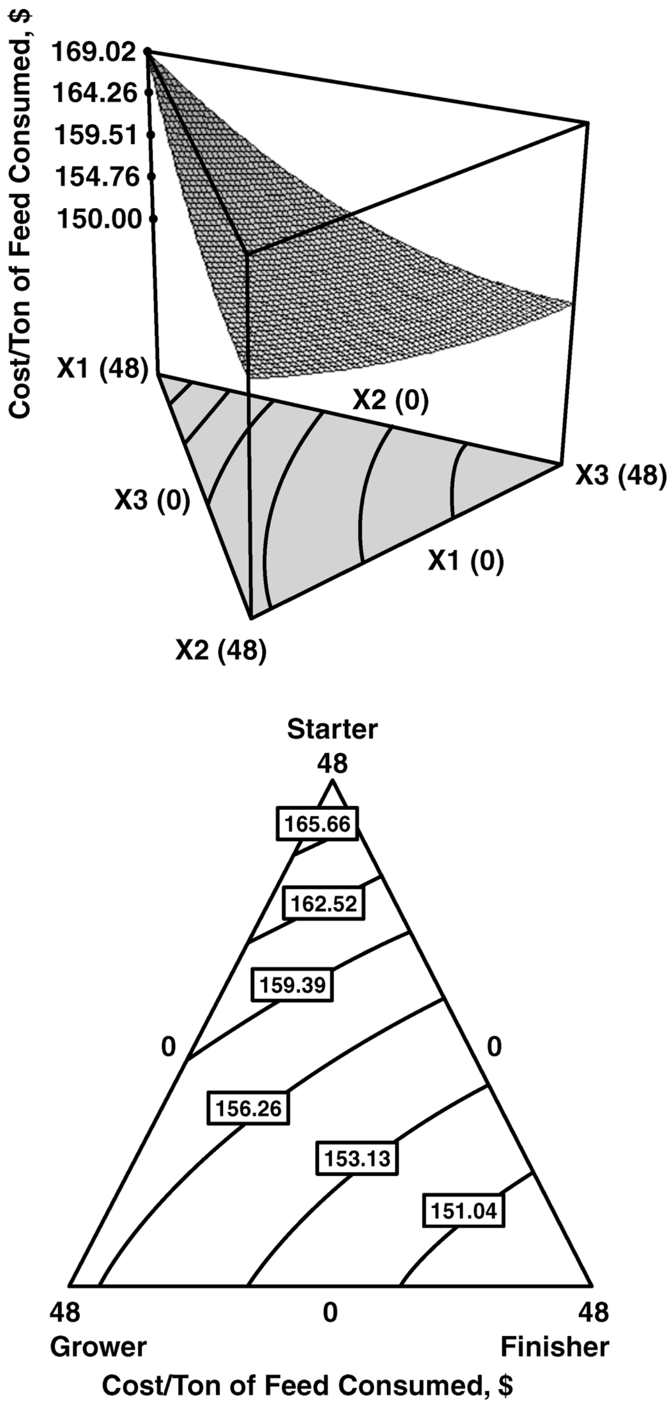

FIGURE 3. Three-dimensional response surface and two-dimensional contour plot for cost of the feed consumed ($). Vertices represent starter (X_1), grower (X_2), and finisher (X_3) diets with a total production period of 48 d.

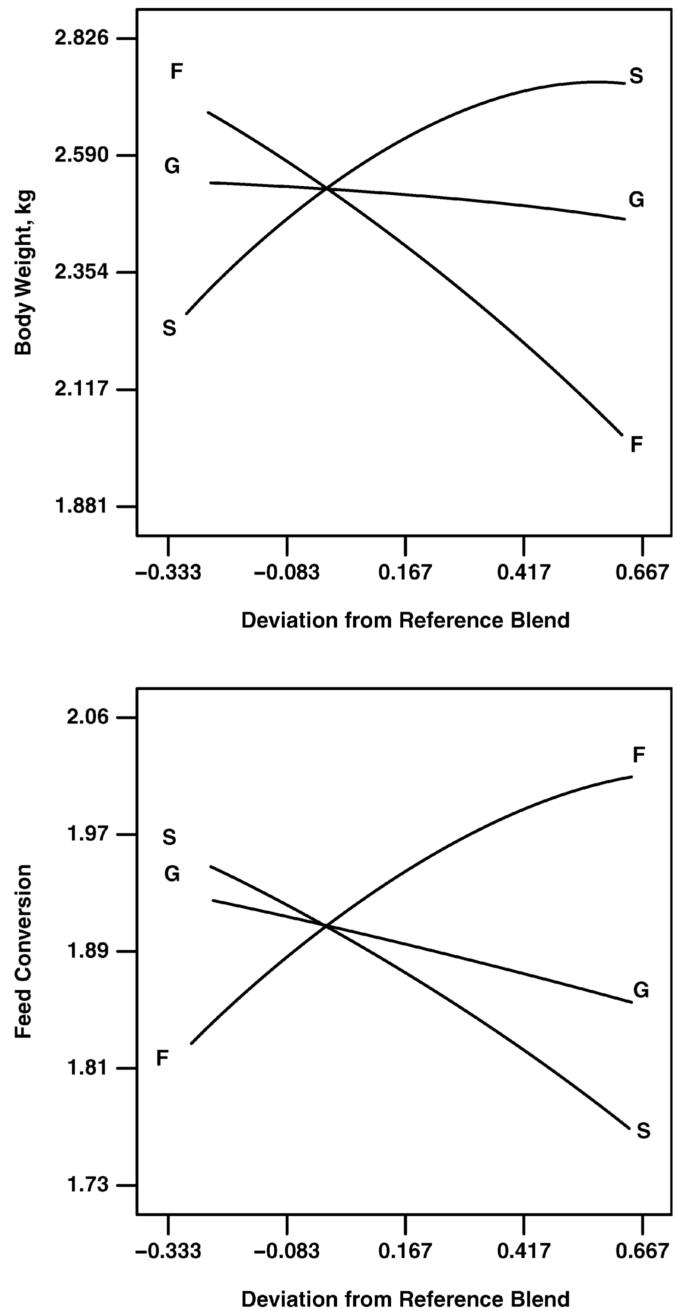

FIGURE 4. Response trace plots (Piepel, 1982) for BW (kg) and feed conversion. Deviation from reference blend (mixture design centroid) for starter (S), grower (G), and finisher (F).

desirable, indicating the model could be used to navigate the design space (Stat-Ease, 2002). The formula for adequate precision is:

$$\text{adequate precision} = \left[\frac{\max(\hat{Y}) - \min(\hat{Y})}{\sqrt{\frac{p(SD)^2}{n}}}\right] \qquad [2]$$

where $\hat{Y}$ is the estimated response, p is the number of model coefficients and n represents the number of experimental runs (60, one run represents each design point and replicate).

Because optimizing the diets involves several responses, a desirability function approach (Derringer and Suich, 1980) was used. The individual desirability functions for the responses were based on the following:

$$\text{desirability (maximized)} = \frac{\text{(optimal solution} - \text{lower limit)}}{\text{upper limit} - \text{lower limit}} \qquad [3]$$

TABLE 4. Mixture design (actual and coded levels) and control for phase feeding (48 d basis) starter, grower, and finisher diets to broilers: Biological measurements recorded at processing[1]

Design point	Actual levels (d) Starter	Grower	Finisher	Processing BW (kg)	Hot carcass (kg)	Dressing (%)	Fat pad (%)	Pectoralis major (kg)	Pectoralis minor (kg)
1	48	0	0	2.942 ± 0.091	2.101 ± 0.078	71.50 ± 1.89	1.35 ± 0.19	0.457 ± 0.043	0.113 ± 0.006
2	0	48	0	2.610 ± 0.096	1.854 ± 0.076	70.98 ± 0.73	1.49 ± 0.22	0.388 ± 0.017	0.090 ± 0.006
3	0	0	48	2.150 ± 0.096	1.484 ± 0.078	68.96 ± 0.91	1.70 ± 0.27	0.271 ± 0.016	0.066 ± 0.005
4	24	24	0	2.872 ± 0.050	2.063 ± 0.040	71.81 ± 0.28	1.56 ± 0.23	0.458 ± 0.020	0.109 ± 0.008
5	24	0	24	2.755 ± 0.063	1.977 ± 0.060	71.70 ± 0.81	1.80 ± 0.26	0.420 ± 0.017	0.097 ± 0.006
6	0	24	24	2.493 ± 0.159	1.763 ± 0.119	70.65 ± 0.46	1.81 ± 0.32	0.355 ± 0.033	0.082 ± 0.008
7	16	16	16	2.757 ± 0.183	1.974 ± 0.144	71.53 ± 0.83	1.70 ± 0.15	0.425 ± 0.027	0.099 ± 0.004
8	32	8	8	2.863 ± 0.072	2.064 ± 0.054	72.08 ± 0.79	1.50 ± 0.32	0.462 ± 0.023	0.109 ± 0.006
9	8	32	8	2.644 ± 0.042	1.895 ± 0.048	71.60 ± 0.79	1.82 ± 0.16	0.402 ± 0.020	0.093 ± 0.008
10	8	8	32	2.526 ± 0.087	1.792 ± 0.073	70.87 ± 0.70	1.99 ± 0.32	0.361 ± 0.026	0.083 ± 0.005

[1]Mean ± SD, design points 1 to 10, n = 6.

where the lower and upper limits are ranges of responses determined by the decision maker, and

$$\text{desirability (minimized)} = 1 - \text{desirability (maximized)} \quad [4]$$

where desirability (maximized or minimized) refers to the decision maker's choice for a maximized or minimized response variable.

The compromise desirability function was the geometric mean of the individual desirability's in the form

$$D = [d_1 \times d_2 \times ...d_n]^{1/n} \quad [5]$$

where d_i is the desirability function for the ith response (i = 1, 2, ..., n). The desirability function for a given response assigns desirability values between 0 (undesirable) and 1 (fully desirable) within a specified range of response values. The combined desirability (D) also takes values between 0 and 1. The desirability function approach is a way to obtain an optimal balance between optimal mixtures for individual responses while maintaining all responses within specified limits. The desirability function optimization was implemented using the Design-Expert software (Stat-Ease, 2002).

In an effort to make the results of the experiment design robust, a propagation of error (POE) technique was incorporated in the compromise desirability value. The aim of POE was to make the experimental results less sensitive to the variation of the input factors (i.e., robust to the time of diet change). The Design-Expert (Stat-Ease, 2002) approach sets controllable factors at levels that reduce variation in the response caused by uncontrollable factors and the variation transmitted from controllable factors (Whitcomb and Anderson, 1996). The calculation results in response surfaces representing the error propagated by the input values over the surface of the response variables (not shown). Therefore, to make the results more robust for practical use, a heuristic assumption was made that the estimated error in making time of change of the S, G, and F diets would be plus or minus 1 d. The POE calculations in this experiment were made on that assumption.

A trace plot (Piepel, 1982; Myers and Montgomery, 1995) was used to estimate the influence of the input variables, S, G, and F, on the responses. The trace plot shows the effects of changing each mixture component while holding all others in a constant ratio. The effect is shown in the plot of changing the input components along an imaginary line from a reference blend, which was defaulted to be the center of the design, to the vertex of design. As the amount of this component increases, the amounts of all of the other components decrease, with the ratios to one another remaining constant. A steep slope or curvature of an input variable indicates a relatively high sensitivity of the response. Variables exhibiting response sensitivity are influential candidates for the axes on 2-D and 3-D contour plots. On the other hand, if the slope of the variable is negligible, the sensitivity of the response is low for that variable (Stat-Ease, 2002).

RESULTS AND DISCUSSION

There is no single answer to the defining of optimum conditions. The optimum conditions, in the context of the fitted mixture models, depend on the priorities, response constraints, and requirements, which are determined by the manager. Therefore, the mixture design approach, as a management decision tool, allows the manager to analyze a number of poultry management feeding scenarios. The following are based on the results of the experiment. There were no significant differences in the 2 blocks of the design, therefore the analysis was based on the values obtained from the 60 pens.

Body Weight, Feed Conversion, and Cost of Feed Consumption

The actual and coded levels for the treatments along with the average BW and feed conversion responses and standard deviations are shown in Table 2. The BW and feed conversion data were fitted to a simplex regression model. Regression coefficient estimates and summary statistics for BW, feed conversion, and the cost of consumed feed are shown in Table 3. With the exception of cost of feed consumed, the LOF responses were not significant

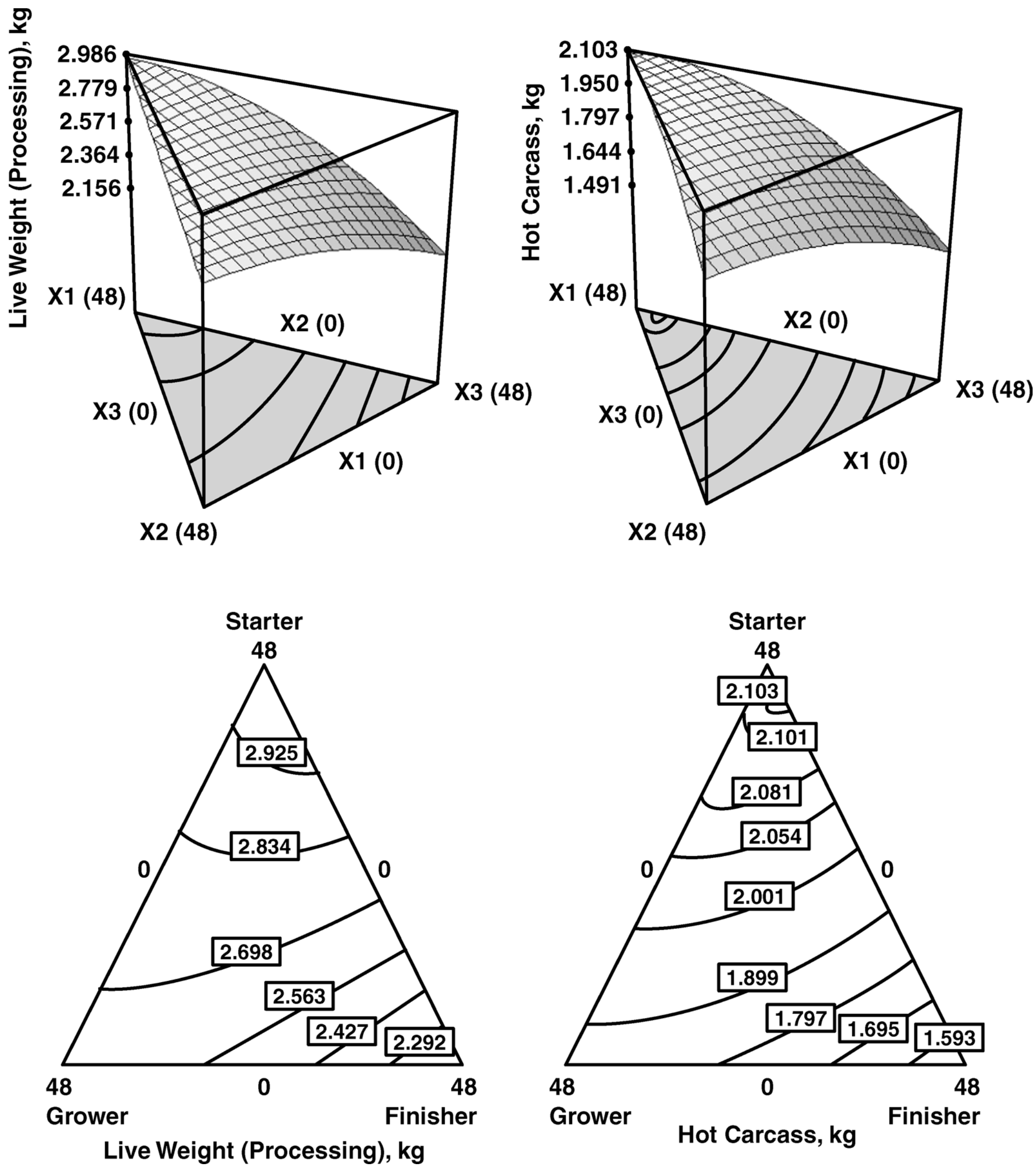

FIGURE 5. Three-dimensional response surfaces and two-dimensional contour plots for live weight (kg) at processing and hot carcass weight (kg). Vertices represent starter (X_1), grower (X_2), and finisher (X_3) diets with a total production period of 48 d.

indicating the models for BW and feed conversion adequately represented the response surface of the data.

The significant LOF for cost of feed consumed indicated that the response data still had some variation that was not explained by the fitted special-cubic model. Despite this, the high R^2 values, and adequate precision values reflect that the model was adequate for analysis of the response surface.

Three-dimensional and contour graphs are shown in Figure 2 for BW and feed conversion, and in Figure 3 for cost of feed consumed. If BW is considered, the contours point to a mixture of S and G (no F) for the optimal BW. The numerical analysis indicated the combination would be 37 d on S and 11 d on G, with an optimal BW of 2.759 kg (desirability of 0.929). The optimal feed conversion would result from S fed singly for the 48 d period with a predicted feed conversion of 1.76 (desirability of 0.899). However, according to Figure 3, the cost for the feed consumed would be high for either of these feeding regimens. For optimum BW, the cost would be \$164.18 and for optimum feed conversion, the cost would be \$168.79. A compromise analysis for all 3 variables (i.e., to maximize BW, minimize feed conversion, and minimize cost of feed consumed) results in a regimen of S (18 d) and G (30 d). The resulting optimum BW, feed conversion, and cost of feed consumed would be 2.680 kg, 1.82, and \$158.77, respectively, with a desirability value of 0.687.

The trace plot (Figure 4) results indicated that BW and feed conversion were not very sensitive to the grower diet (G). In other words, the horizontal line representing the deviation of the G diet response from the centroid treatment had little effect on BW or feed conversion responses as compared with S and F diets. The trace plots in Figure 4 show that increasing S has the strongest effects

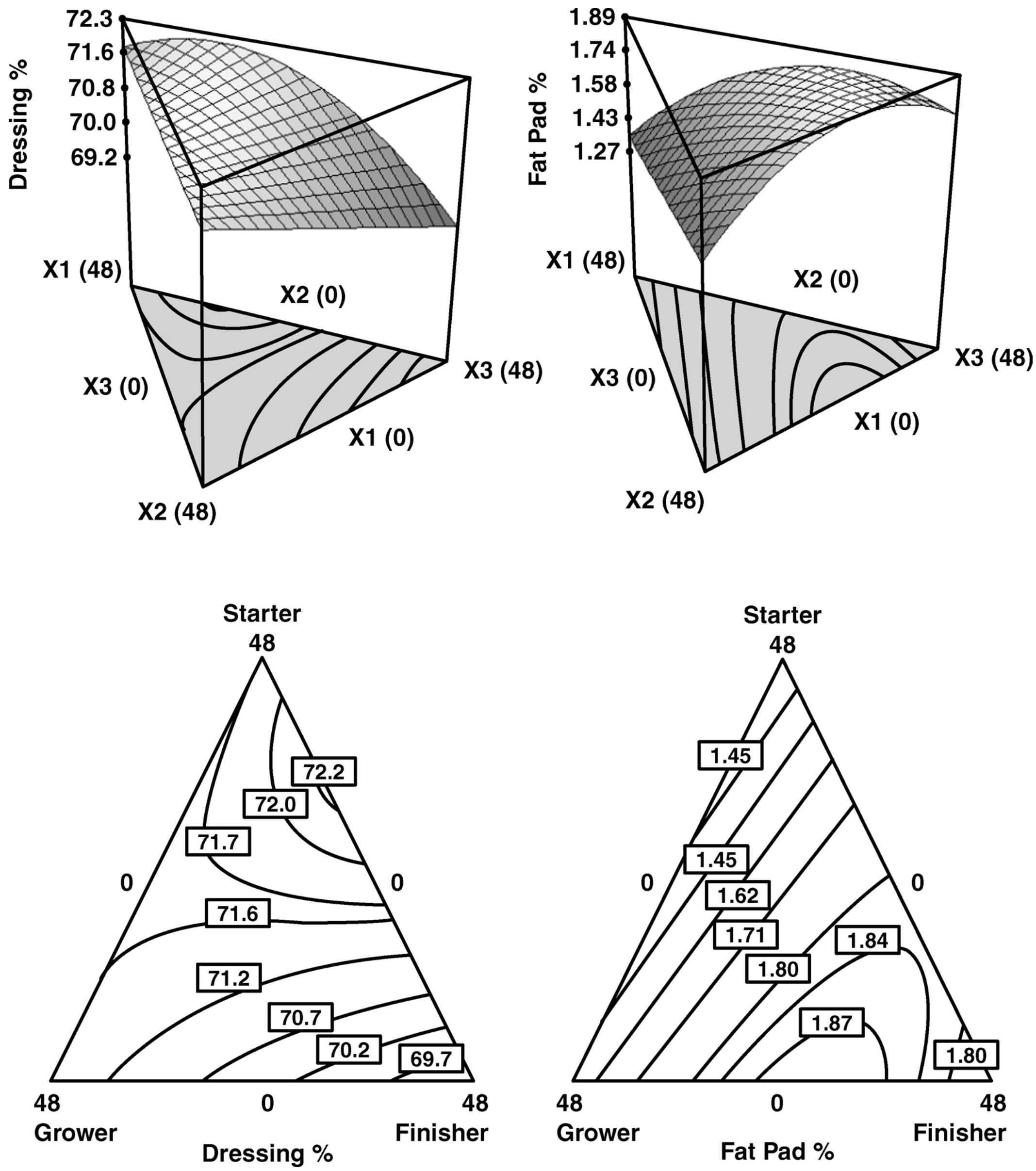

FIGURE 6. Three-dimensional response surfaces and two-dimensional contour plots for dressing percentage and fat pad percentage. Vertices represent starter (X_1), grower (X_2), and finisher (X_3) diets with a total production period of 48 d.

on increasing BW and decreasing feed conversion. Decreasing F increases BW and decreases feed conversion. Thus, G having negligible effects on BW and feed conversion allows it to vary and offset higher levels of S and lower levels of F and still maintain the 48 d total (Piepel, personal communication).

Processing Variables

The actual times of providing the treatments along with the processing measurements and standard deviations are shown in Table 4. Simplex regression models were fit to the 6 × 10 = 60 data values for each processing response. Regression coefficients for the BW at processing and the carcass quality measurements analyzed with coded levels and converted to actual time level coefficients are shown in Table 5. The model LOF responses were not statistically significant indicating the models for processing responses adequately represented the data. With the exception of dressing percentage and fat pad percentage, the process variables had R^2 values at or near 0.80. In general, all processing responses, including the dressing and fat pad percentages, had adequate precision values that were greater than 4 indicating that the models for each were adequate for analysis of the response surface of the mixture design.

Three-dimensional and contour graphs are shown for processing live weight and hot carcass weight (Figure 5), dressing percentage and fat pad percentage (Figure 6), and pectoralis major and pectoralis minor responses (Figure 7). The contour and 3-D responses show that live weight data slope toward the starter vertex, which represents S being fed for all of the 48 d. The optimal live weight was calculated at 2.97 kg with a desirability of

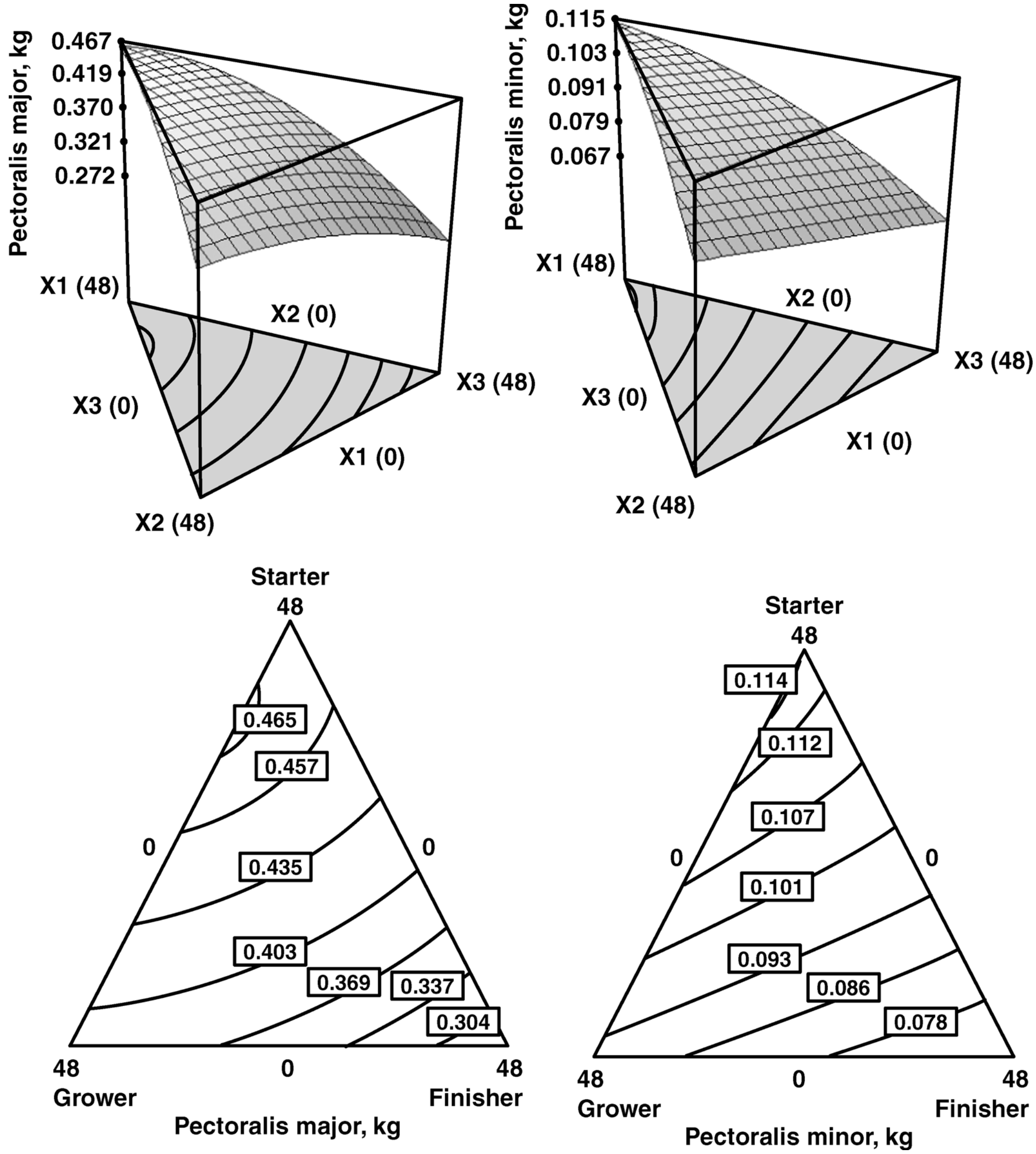

FIGURE 7. Three-dimensional response surfaces and two-dimensional contour plots for pectoralis major and pectoralis minor weights (kg). Vertices represent starter (X_1), grower (X_2), and finisher (X_3) diets with a total production period of 48 d.

0.86. The optimal hot carcass weight was a combination of a period of time (44 d) on S and a shorter time (4 d) on F. The calculated weight of the hot carcass was 2.104 kg with a desirability value of 0.826. The dressing percentage had a calculated value of 72.2% with S being fed for 34 d and F fed for 14 d, and a desirability value of 0.808. The G diet was not included in the optimal calculation. The calculation for the fat pad percentage was found to be minimal (1.36%) when the S diet was fed for all of the 48 d (desirability was 0.803). The components of the breast muscle, pectoralis major, were calculated to be maximal (0.466 kg) when S and G were fed for 37 and 11 d, respectively (desirability was 0.851). Pectoralis minor portion of the breast muscle was calculated to be maximal (0.114 kg) when S was fed for 45 d and G fed for 3 d with a desirability function of 0.887.

When considered individually, each of the production and processing variables has different optimal conditions. An assumption was made that the manager would want to seek a balance for the combination of production and processing variables. Constraints for defining the numerical optimization analysis of the S, G, and F inputs, and production and processing output variables are shown in Table 6. The Design-Expert program allows the weighting of the upper and lower limits of the input and output variables and indication of relative importance of variables. For this study, the weights and importance were maintained at the default levels of 1 and 3, respectively. Propagation of error values were included to make the result robust. When all factors were considered, the compromise solution that would balance the production and processing variables was to feed the broilers S and

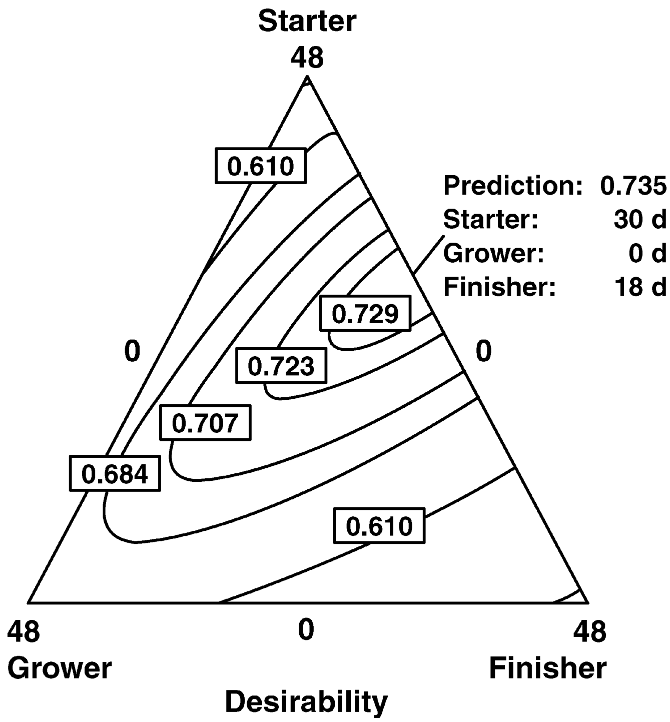

FIGURE 8. Two-dimensional contour plot for compromise desirability function with predicted optimal response. Vertices represent starter, grower, and finisher diets with a total production period of 48 d.

F diets for 30 and 18 d, respectively, with a resulting desirability value of 0.735 (Table 6). The desirability function was graphed in Figure 8.

The purpose of phase feeding is to provide adequate nutrients at specific points in the physiological age of the bird to meet managerial goals. Vandegrift et al. (2003) conducted a cluster analysis of daily BW and feed intake velocities of broilers using Kohonen neural networks. The purpose was to analyze the velocities for an indication when a change in nutrient requirement might occur. Two to five clusters were investigated. Focus was made on 3 clusters because of the NRC (1994) grouping of nutrient requirement into 3 phases. The BW and feed intake velocities clustered very well into 3 clusters indicating natural breaks in the growth process. The feed intake velocities were the most definitive. The Vandegrift approach indicated that time on the diets would be 20 d on S, 10 d on G, and 18 d on F. Relative to the current study, it should be noted that the data clustered very well into 2 clusters. From his thesis, Vandegrift (2002) found the time on S would be 25 d and time on F would be 23 d, based on 2 clusters of the feed intake velocity.

This paper has introduced the concept of considering phase feeding as a mixture design with the times of feeding diets as a proportion of the total amount of time the birds are in production. It is recognized that production times other than 48 d may be required (Gehle et al., 1974; Warren and Emmert, 2000; Pope and Emmert, 2001; Pope et al., 2002) perhaps to meet specific weight goals (Saleh et al., 1996; 1997a,b). Mixture designs are specifically set up to meet a specific amount. The specific amount in this case is 48 d, that is, all of the time proportions must add up to 48 d. When simultaneous comparisons of other times (including 48 d) are wanted, then the experiment

TABLE 5. Regression coefficient estimates for coded (SE) and actual values of phase feeding (48-d basis) of starter (S), grower (G), and finisher (F) diets to broilers: Biological measurements recorded at processing

			Regression coefficient estimate			
Component	Processing BW	Hot carcass weight	Dressing (%)	Fat pad (%)	Pectoralis major	Pectoralis minor
Actual values						
S	0.0619	0.0437	1.494	0.0283	0.00954	0.00237
G	0.0548	0.0385	1.490	0.0326	0.00802	0.00189
F	0.0449	0.0311	1.442	0.0360	0.00567	0.00140
S × G	—	0.000131	—	—	0.0000607	0.0000121
S × F	0.000354	0.000313	0.00254	0.000443	0.0000977	0.0000139
G × F	0.000183	0.000154		0.000409	0.0000412	—
Coded values (SE)						
S	2.97 (0.036)	2.10 (0.032)	71.71 (0.32)	1.36 (0.090)	0.46 (0.00978)	0.11 (0.00246)
G	2.63 (0.036)	1.85 (0.032)	71.50 (0.027)	1.57 (0.090)	0.39 (0.00978)	0.091 (0.00219)
F	2.16 (0.041)	1.49 (0.032)	69.23 (0.32)	1.73 (0.10)	0.27 (0.00978)	0.067 (0.00219)
S × G	—	0.30 (0.15)	—	—	0.14 (0.045)	0.028 (0.011)
S × F	0.082 (0.19)	0.72 (0.15)	5.85 (1.64)	1.02 (0.46)	0.23 (0.045)	0.032 (0.011)
G × F	0.421 (0.19)	0.36 (0.15)	—	0.94 (0.46)	0.095 (0.045)	—
Statistical values[1,2]						
Mean	2.66	1.90	71.17	1.67	0.40	0.094
SD	0.103	0.081	0.91	0.26	0.025	0.006193
CV	3.89	4.26	1.27	15.29	0.621	6.57
R^2	0.831	0.8406	0.4588	0.3106	0.8499	0.8486
Adjusted R^2	0.819	0.8259	0.4598	0.2604	0.8360	0.8346
Predicted R^2	0.799	0.8044	0.3433	0.1759	0.8114	0.8113
MSE	0.107	0.006516	0.82	0.065	0.006168	0.00003836
LOF P-values	0.386 NS	0.855 NS	0.528 NS	0.266 NS	0.888 NS	0.928 NS
Adequate precision	27.2	23.828	11.551	7.135	23.699	24.531

[1]Statistical values are related to the coded value analysis.

[2]MSE = mean square error; LOF = lack of fit.

TABLE 6. Numerical constraint optimization of mixture design for phase feeding of starter, grower, and finisher diets to broilers (48 d basis)

Variable[1]	Goal	Optimization constraints Lower limit	Upper limit	Optimal solution	Desirability[2]
Starter (d)	In range	0	48	30	—
Grower (d)	In range	0	48	0	—
Finisher (d)	In range	0	48	18	—
BW (kg)	Maximize	1.881	2.826	2.615	0.777
POE (BW) (kg)	Minimize	0.071	0.077	0.071	0.940
Feed conversion	Minimize	1.73	2.06	1.90	0.475
POE (feed conversion)	Minimize	0.034	0.035	0.034	0.782
Processing BW (kg)	Maximize	2.014	3.125	2.850	0.752
POE (processing BW) (kg)	Maximize	0.104	0.111	0.104	0.936
Hot carcass weight (kg)	Maximize	1.366	2.259	2.036	0.750
POE (hot carcass weight) (kg)	Minimize	0.081	0.087	0.081	0.959
Dressing percentage (%)	Maximize	67.8	73.2	72.1	0.796
POE (dressing percentage) (%)	Minimize	0.91	0.92	0.91	0.940
Fat pad percentage (%)	Minimize	1.08	2.48	1.74	0.530
POE (fat pad percentage) (%)	Minimize	0.255	0.257	0.256	0.908
Pectoralis major (kg)	Maximize	0.243	0.505	0.440	0.750
POE (pectoralis major) (kg)	Minimize	0.025	0.027	0.025	0.974
Pectoralis minor (kg)	Minimize	0.058	0.121	0.103	0.286
POE (pectoralis minor) (kg)	Minimize	0.0063	0.0065	0.0063	0.919
Cost per ton of feed consumed ($)	Minimize	150.00	168.80	157.23	0.616
POE (cost per ton of feed consumed) ($)	Minimize	0.105	0.920	0.377	0.668
Desirability (compromise)[3]	Maximize	0	1	—	0.735

[1]POE = propagation of error, to minimize variation in responses (Stat-Ease, 2002). Based on ± 1 d variation in the time for changing starter, grower, and finisher diets.

[2]Desirability (maximized) = (optimal solution − lower limit)/(upper limit-lower limit).

Desirability (minimized) = 1 − desirability (maximized).

[3]Desirability (compromise) = $[d_1 \times d_2 \times ...d_n]^{1/n}$, where d_n= individual desirability value; n = number of desirability values. The calculation is a geometric mean of the variable desirability function.

becomes a mixture-amount experiment. Piepel and Cornell (1985) have addressed the requirement of simultaneous variations in the amount so that the amount can be included as a variable.

The results of this study suggest that mixture designs can be effectively used to study phase feeding of broilers. The mixture models can be used to find the balance of the provision of diets that will provide optimal production and processing performance. Based on the constraints imposed in this experiment, it was found that of the 3 diets examined, S, G, and F, the production and processing responses were less sensitive to the grower diet.

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